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## 13. ABSTRACT (Maximum 200 words)

The general goal of this research was the generation, manipulation and characterization of coherent and non-classical matter waves, including atom lasers. The research involved both a theoretical and an experimental component.

Major achievements from the Meystre group include the theory of a binary-collision atom laser, new proposals in nonlinear atom optics, in particular the optical control of matter waves, matter-wave superradiance and coherent matter-wave amplification. These are applications of the nonlinear mixing between optical and matter waves, which have recently seen their first experimental verifications by groups at MIT, NIST and U. Tokyo. This work has also lead to a new proposal for atom holography. In addition, we have started to develop the coherence theory of matter waves and of the cross-coherence between optical and matter waves.

Major results from the Jessen group include an in-depth study of practical avenues for single-atom quantum state engineering, and development of a novel proposal for entanglement engineering and quantum logic in optical lattices. Our most noteworthy experimental achievements include the development of efficient methods to load and trap atoms in far-of-resonant optical lattices, and the first demonstration of Raman sideband cooling of neutral Cs atoms to the ground state of an optical lattice. Most recently we have completed an experiment on coherent quantum tunneling and macroscopic quantum coherence in optical double-well potentials, and have initiated a new experiment to reconstruct the complete internal state of ultracold atomic wavepackets.

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## **I. Statement of problem studied**

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Major results from the Jessen group include an in-depth study of practical avenues for single-atom quantum state engineering, and development of a novel proposal for entanglement engineering and quantum logic in optical lattices. Our most noteworthy experimental achievements include the development of efficient methods to load and trap atoms in far-of-resonant optical lattices, and the first demonstration of Raman sideband cooling of neutral Cs atoms to the ground state of an optical lattice. Most recently we have completed an experiment on coherent quantum tunneling and macroscopic quantum coherence in optical double-well potentials, and have initiated a new experiment to reconstruct the complete internal state of ultracold atomic wavepackets.

## **II. Summary of most important results**

### **Meystre group.**

The last few years have been extraordinary ones for AMO physics. Atomic manipulation has reached an exquisite degree of sophistication, both at the single-particle level and in many particle ensembles such as Bose-Einstein condensates and quantum degenerate Fermi systems. As a result, many of the dreams of five to ten years ago are rapidly becoming reality. One such dream was that of an atom laser, which has now been realized in several laboratories [1]. But just as exciting perhaps are the experimental verification of atomic four-wave mixing [2], the mixing of optical and matter waves, resulting in matter-wave superradiance[3] and the demonstration of a phase-coherent matter-wave amplifier [4], and the generation of atomic solitons in condensates [5].

These developments have been especially gratifying for us. We had predicted as early as 1993 the possibility of nonlinear atom optics [6], and its experimental verification was quite a thrill. In several papers carried out in the framework of the present proposal, we also investigated theoretically the nonlinear coupling between optical and matter waves, first in the so-called Collective Atomic Recoil Laser (CARL) where a cavity was used to select one or a few modes of the electromagnetic field [7]. One of our predictions was that it would be possible to optically

influence and control the quantum statistical properties of a matter-wave field, and to coherently amplify such a field. When Ketterle's group at MIT informed us of their matter-wave superradiance results, it became immediately clear that all of our theory could readily be adapted to this situation, and most of its conclusions extended to the new geometry with very little change. In addition, we have been able to rapidly extend this work to predict the shot-to-shot fluctuations in the output of the system, and attribute their origin to quantum fluctuations, both in the electromagnetic and matter-wave fields [8]. In recent work, the MIT group has also confirmed our prediction that optical and matter-wave amplification go hand in hand, and are two facets of the same physics [9].

These various developments, while validating our work in a much more spectacular way than we would have expected, also positioned us perfectly to rapidly move into new directions as they opened up. The validation of our quantum optical approach to the physics of quantum degenerate systems, and the experimental verification of the fact that at ultracold temperatures, collisions act indeed as a coherent nonlinear medium for the atoms, open up a number of new avenues that we are now aggressively exploring. Particularly attractive possibilities include the optical control of the state of the Schrödinger field, as well as the generation of a quantum entanglement between them. This would be of interest for many applications, since it is notoriously much easier to store atoms than light, but light is a much more convenient way to transport information. In this context, we believe that our recent extension of coherence theory to handle the joint coherence properties of optical and matter-wave fields [10] will prove beneficial.

### **Jessen group**

The general theme of our research has been the development of methods for quantum coherent control of laser trapped atoms [11]. We have focussed our efforts on atoms trapped deep in the Lamb-Dicke regime in far-off-resonance optical lattices. In some respects this system is quite similar to atomic ions in ion traps, and it is possible to borrow techniques (sideband cooling, rotation of the state vector between pairs of spin/vibrational states) from the ion trap community [12]. We have pioneered a new method by which the required Raman couplings can be designed directly into an optical potential, thus greatly reducing the complexity of such experiments.

As a starting point for sideband cooling and quantum control experiments, it is desirable to prepare atoms as close as possible to the ground vibrational state of a single magnetic sublevel. In two experiments we have shown how laser cooling and state preparation in a 1D optical lattice can be enhanced with magnetic fields [13], and how atoms can be adiabatically loaded into a far-off-resonance lattice with negligible increase in vibrational excitation [14].

The principal goal of our research has been the demonstration of a technique for resolved-sideband cooling of Cs atoms in a far-off-resonance lattice. We have developed a simple and elegant cooling scheme, in which Raman coupling between magnetic sublevels is built into the optical lattice potential [11], and a small external magnetic field used to tune the requisite vibrational states into degeneracy. In the first experimental demonstration of resolved-sideband Raman cooling [15] we trapped  $10^6$  atoms in the potential wells of a 2D optical lattice, and cooled them to a mean vibrational excitation of 0.008 per degree of freedom. This corresponds to a population of the two-dimensional vibrational ground state close to 98%. Adiabatic cooling

produced free atom kinetic temperatures as low as 120 nK, well below the single photon recoil limit. Subsequent work by Vuletic and Chu [16] and by Weiss [17] have implemented our basic scheme in 3D lattices with very high density Cesium samples, and succeeded in cooling to phase space densities approaching BEC. Ultimately, it seems likely that our technique will become an essential element of Cesium BEC and atom lasers.

The second major goal of our research has been to demonstrate and study coherent quantum tunneling between optical potential wells. We have focussed in particular on optical double-well potentials in a 1D lin- $\theta$ -lin far-off-resonance optical lattice [11]. Preparing the atoms initially on one side of the double-well, we have observed clear Rabi oscillations between mesoscopically distinct left- and right-localized wavepackets, separated by  $\sim 150$  nm [18]. This type of quantum coherent evolution has long served as a paradigm for non-classical dynamics, and in our atom optics implementation it can be studied with minimal decoherence, controlled dissipation and the whole toolbox characteristic of quantum optics: pure state preparation, controlled unitary evolution and quantum state measurement. In future experiments we hope to observe quantum coherent evolution over many Rabi periods, and to reintroduce engineered dissipation and continuous measurement in order to study the fundamental process of decoherence and the quantum/classical transition. The latter is particularly intriguing, since the classical dynamics is chaotic [19] and our system allows to study the effect of decoherence on the emergent nonlinear behavior [20].

The ability to accurately measure an unknown quantum state is a necessary complement to quantum state control. Because the internal and external degrees of freedom of an atomic wavepacket become entangled in many types of neutral atom traps, it is often possible to use the atomic internal state as a “meter” to observe the center-of-mass dynamics. Towards the end of the grant period we have worked to implement a scheme to reconstruct the entire ground state density matrix of an atom through repeated Stern-Gerlach measurements [21]. At the time of writing this report we have carried out a first proof-of-principle experiment. We expect the ability to directly measure atomic coherences to be of great value for studies of decoherence, and for the evaluation of neutral atom quantum logic gates.

One of the most exciting developments during the grant period has emerged from a collaboration with Profs. Deutsch and Caves at the University of New Mexico. For a number of years we have been searching for means to control the joint quantum state of coupled atom pairs. Starting from Meystre’s work on dipole-dipole coupling in optical lattices [22], we have shown that it is possible to obtain substantially coherent atom-atom coupling based on dipole-dipole interactions between strongly localized wavepackets. We have further developed a scheme to use atoms trapped in optical lattices as qubits and to perform pairwise entangling quantum logic operations between them [23,24]. This raises prospects for small-scale quantum information processing [25], and for spectroscopy and atom interferometry with sensitivity below the standard quantum limit [12,26]. The latter is particularly intriguing, since the optical lattice lends itself naturally to massive parallelism (in the classical sense) and might allow efficient entanglement of very large number of particles. We are still working out the details of the basic quantum logic protocol, including a full description of the molecular physics at the heart of the atom-atom interaction, but our results so far indicates that a quantum phase gate can be implemented with a fidelity of order 0.95 with currently existing optical lattice technology [27]. This is sufficient to entangle a non-

trivial number of atoms, and we are hopeful that further developments can improve the fidelity substantially.

### III. List of publications and technical reports

#### Meystre group

1. S. Pötting, E. S. Lee, W. Schmitt, I. Rumyantsev, B. Mohring and P. Meystre, "Quantum coherence and interaction-free measurements", submitted to Phys. Rev. A, Rapid Commun.
2. H. Pu and P. Meystre, "Creating macroscopic atomic EPR states from Bose condensates", submitted to Phys. Rev. Lett.
3. J. Heurich, H. Pu, M. G. Moore and P. Meystre, "Instabilities and self-oscillations in atomic four-wave mixing", submitted to Phys. Rev. A.
4. E. V. Goldstein, M. G. Moore, H. Pu and P. Meystre, "Eliminating the mean-field shift in Bose-Einstein condensates," submitted to Phys. Rev. Lett.
5. M. G. Moore and P. Meystre, "Generating entangled atom-photon pairs from Bose-Einstein condensates," submitted to Phys. Rev. Lett.
6. S. Pötting, O. Zobay, P. Meystre and E. M. Wright, "Magneto-optical control of bright atomic solitons", to be published in J. Mod. Optics.
7. M. G. Moore and P. Meystre, "Parametric amplification of coupled atomic and optical fields", to be published in "Coherence in Light-Matter Interaction", a volume in the Memory of D. F. Walls, edited by H. J. Carmichael, R. J. Glauber and M. O. Scully, to be published by Springer Verlag.
8. G. A. Pratavera, J. Zapata and P. Meystre, "Higher-order mutual coherence of optical and matter waves", to be published in Phys. Rev. A.
9. J. Heurich, M. G. Moore and P. Meystre, "Cavity quantum optics and the 'free-atom laser' ", Optics Commun. **179**, 549 (2000).
10. S. Letokhov and P. Meystre, editors, "Advances in Laser Physics", A Volume in the Memory of Peter Franken, Laser Science and Technology Second Series, Volume 1, Harwood Academic Publishers, Amsterdam (2000).
11. E. V. Goldstein, M. G. Moore and P. Meystre, "Nonlinear Optics of Matter Waves", in "Advances in Laser Physics", edited by V. S. Letokhov and P. Meystre, Laser Science and Technology Second Series Volume 1, Harwood Academic Publishers, Amsterdam (2000), p. 117.

12. E. V. Goldstein, M. G. Moore and P. Meystre, "Nonlinear Manipulation and Control of Matter Waves", *Laser Physics* **10**, 8 (2000).
13. M. G. Moore and P. Meystre, "Theory of superradiant scattering of laser light from Bose-Einstein condensates", *Phys. Rev. Lett.* **83**, 5202 (1999).
14. G. A. Pratavia, E. V. Goldstein and P. Meystre, "Mutual coherence of optical and matter waves", *Phys. Rev. A* **60**, 4846 (1999).
15. E. S. Lee, C. Geckeler, J. Heurich, A. Gupta, Kit-Iu Cheong, S. Secrest and P. Meystre, "Dark states of dressed Bose-Einstein condensates", *Phys. Rev. A* **60**, 4006 (1999).
16. O. Zobay, E. V. Goldstein and P. Meystre, "Atom holography", *Phys. Rev. A* **60**, 3999 (1999).
17. M. G. Moore, O. Zobay and P. Meystre, "Quantum optics of a Bose-Einstein condensate coupled to a quantized light field", *Phys. Rev. A* **60**, 1491 (1999).
18. G. J. Yang, O. Zobay and P. Meystre, "Two-atom dark states in electromagnetic cavities", *Phys. Rev. A* **59**, 4012 (1999).
19. E. V. Goldstein and P. Meystre, "Quantum theory of atomic four-wave mixing in Bose-Einstein condensates", *Phys. Rev. A* **59**, 3896 (1999).
20. M. G. Moore and P. Meystre, "Optical control and entanglement of atomic Schrödinger fields", *Phys. Rev. A* **59**, R1754 (1999).
21. E. V. Goldstein and P. Meystre, "Phase conjugation of multicomponent Bose-Einstein condensates", *Phys. Rev. A* **59**, 1509 (1999).
22. O. Zobay, E. M. Wright and P. Meystre, "Creation of gap solitons in Bose-Einstein condensates", *Phys. Rev. A* **59**, 643, (1999).
23. M. G. Moore and P. Meystre, "Effects of atomic diffraction on the collective atomic recoil laser", *Phys. Rev. A* **58**, 3248 (1998).
24. E. V. Goldstein, O. Zobay and P. Meystre, "Coherence of atomic matter-wave fields", *Phys. Rev. A* **58**, 2373 (1998).
25. E. V. Goldstein, E. M. Wright and P. Meystre, "Detection of condensate vortex states", *Phys. Rev. A* **58**, 576 (1998).
26. O. Zobay and P. Meystre, "Phase dynamics in a binary-collision atom-laser scheme", *Phys. Rev. A* **57**, 4710 (1998).
27. E. V. Goldstein and P. Meystre, "Atomic detection and matter-wave coherence", *Phys. Rev. Lett.* **80**, 5036 (1998).

28. E. V. Goldstein, E. M. Wright and P. Meystre, "Dressed Bose-Einstein condensation in high-Q cavities", *Phys. Rev. A* **57**, 1223(1998).
29. M. Guzman and P. Meystre, "Dynamical effects of the dipole-dipole interaction in 3-dimensional optical lattices", *Phys. Rev. A* **57**, 1139 (1998).

#### **Jessen group**

31. D. L. Haycock, P. Alsing, I. H. Deutsch, J. Grondalski and P. S. Jessen, "Mesoscopic quantum coherence in an optical lattice", submitted to *Phys. Rev. Lett.* (2000).
32. I. H. Deutsch, G. K. Brennen and P. S. Jessen, "Quantum Computing with Neutral Atoms in an Optical Lattice", to appear in *Fortschritte der Physik* (October 2000).
33. I. H. Deutsch, P. M. Alsing, J. Grondalski, S. Ghose, P. S. Jessen and D. L. Haycock, "Quantum Transport in Magneto-Optical Double-Potential Wells", to appear in *J. Opt. B: Quantum Semiclass.* (2000).
34. G. K. Brennen, I. H. Deutsch and P. S. Jessen, "Entangling Dipole-Dipole Interactions and Quantum Logic in Optical Lattices", *Phys. Rev. A* **61**, 062309-1 (2000).
35. I. H. Deutsch, G. K. Brennen, J. Grondalski, C. M. Caves, P. S. Jessen, S. E. Hamann, D. L. Haycock and G. Klose, "Sideband Cooling, State Control and Quantum Logic in Optical Lattices", in "Laser Spectroscopy, XIV International Conference", eds R. Blatt, J. Eschner, D. Liebfried and F. Schmidt-Kaler (World Scientific 1999).
36. G. K. Brennen, C. M. Caves, P. S. Jessen and I. H. Deutsch, "Quantum Logic Gates in Optical Lattices", *Phys. Rev. Lett.* **82**, 1060 (1999).
37. S. E. Hamann, D. L. Haycock, I. H. Deutsch and P. S. Jessen, "Resolved-sideband Raman cooling to the ground state of an optical lattice", *Phys. Rev. Lett.* **80**, 4149 (1998).
38. I. H. Deutsch and P. S. Jessen, "Quantum State Control in Optical Lattices", *Phys. Rev. A* **57**, 1972 (1998).
39. D. L. Haycock, S. E. Hamann, G. Klose, G. Raithel and P. S. Jessen, "Enhanced laser cooling and state preparation in an optical lattice with a magnetic field", *Phys. Rev. A* **57**, R705 (1998).
40. D. L. Haycock, S. E. Hamann, G. Klose and P. S. Jessen, "Atom Trapping in Deeply Bound States of a Far-Off-Resonance Optical Lattice", *Phys. Rev. A* **55**, R3391 (1997).
41. M. Gatzke, G. Birkel, P. S. Jessen, A. Kastberg, S. L. Rolston and W. D. Phillips, "Temperature and localization of atoms in three-dimensional optical lattices", *Phys. Rev. A* **55**, R3987 (1997).

42. D. L. Haycock, S. E. Hamann, G. Klose and P. S. Jessen, "Atom trapping in the Lamb-Dicke regime in a far-off-resonance optical lattice", Proc. SPIE **2995**, 163 (1997).

#### **IV. List of all participating scientific personnel**

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#### **V. Report of inventions**

Invention disclosure: P. Meystre, M. G. Moore and O. Zobay, "Quantum microfabrication by matter-wave or optical holography, " November 1998.

#### **VI. bibliography**

- [1] M. O. Mewes et al, Phys. Rev. Lett. **78**, 582 (1997); B. P. Anderson and M. A. Kasevich, Science **282**, 1686 (1998); I. Bloch et al, Phys. Rev. Lett. **82**, 3008 (1999); E. W. Hagley et al, Science **283**, 1706 (1999).
- [2] L. Deng et al, Nature **398**, 218 (1999).
- [3] S. Inouye et al, Science **285**, 571 (1999).
- [4] S. Inouye et al, Nature **402**, 64 (1999); M. Kozuma et al, Science **286**, 2309 (1999)
- [5] S. Burger et al, Phys. Rev. Lett. **83**, 5198 (1999); J. Denschlag et al, Science **287**, 97 (2000).

- [6] G. Lenz, P. Meystre and E. M. Wright, Phys. Rev. Lett. **71**, 3271 (1993).
- [7] M. G. Moore and P. Meystre, Phys. Rev. A **58**, 3248 (1998) and *ibid* **59**, R1754 (1999).
- [8] M. G. Moore and P. Meystre, Phys. Rev. Lett. **83**, 5202 (1999).
- [9] S. Inouye et al, "Amplification of light and atoms in a Bose-Einstein condensate", arXiv preprint cond-mat/0006455.
- [10] G. A. Pratavia, E. V. Goldstein and P. Meystre, Phys. Rev. A **60**, 4846 (1999); G. A. Pratavia, J. Zapata and P. Meystre, Phys. Rev. A, in print (2000).
- [11] I. H. Deutsch and P. S. Jessen, Phys. Rev. A **57**, 1972 (1998).
- [12] See for example D. Wineland *et al.*, Fortschr. Phys. **46**, 363 (1998), and references therein.
- [13] D. L. Haycock *et al.*, Phys. Rev. A **57**, R705 (1998).
- [14] D. L. Haycock *et al.*, Phys. Rev. A **55**, R3391 (1997).
- [15] S. E. Hamann *et al.*, Phys. Rev. Lett. **80**, 4149 (1998).
- [16] A. J. Kerman *et al.*, Phys. Rev. Lett. **84**, 439 (2000).
- [17] D. S. Weiss, private communications.
- [18] D. L. Haycock *et al.*, submitted to Phys. Rev. Lett.
- [19] I. H. Deutsch *et al.*, to appear in J. Opt. B: Quantum Semiclass. (2000).
- [20] S. Habib, K. Shizume and W. H. Zurek, Phys. Rev. Lett. **80** 4361 (1998).
- [21] R. G. Newton and B.-L. Young, Ann. Phys. **49**, 393 (1968).
- [22] E. V. Goldstein, P. Pax and P. Meystre, Phys. Rev. A **53**, 2604 (1996).
- [23] G. K. Brennen *et al.*, Phys. Rev. Lett. **82**, 1060 (1999).
- [24] G. K. Brennen, I. H. Deutsch and P. S. Jessen, Phys. Rev. A **61**, 062309-1 (2000).
- [25] "Introduction to Quantum Computation and Information", edited by H.-K. Lo, S. Popescu, and T. Spiller (World Scientific, Singapore, 1998).
- [26] S. F. Huelga *et al.*, Phys. Rev. Lett. **79**, 3865 (1997).

- [27] I. H. Deutsch, G. K. Brennen and P. S. Jessen, "Quantum Computing with Neutral Atoms in an Optical Lattice", to appear in Fortschritte der Physik (October 2000).